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Some aspects of CFRP steel structures reinforcement in civil engineering

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Abstract

The FRP materials application in various branches of technology is under examination for at least for about half a century. In civil engineering the most attention was given to practical aspects of FRP application for RC (reinforced concrete) elements strengthening. As for steel structures there is much less done in this field, high elastic modulus of steel being one of the critical points for this delay. Bonding between the adherents represents another problem point when dealing with the FRP reinforcement of steel structures. In RF there are few works concerning this problem.

In this paper the case of axial tension is considered and formulae for the ultimate bonding layer length and other parameters are given with worked numerical examples. Also some prospects of application of CFRP in building are discussed.

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Keywords: steel structures; carbon fiber reinforced polymers (CFRP); CFRP Strengthening, axial tension; adhesion; bonded connection

1. General

Carbon fiber reinforced polymers (CFRP) application in strengthening structural elements is being rapidly developed in recent several decades. Compared to conventional using steel variants of reinforcement the CFRP have much higher strength-to-weight ratio, are easy to handle and apply, don't need any heavy lifting and handling equipment. These qualities make CFRP to be advantageous for repair, retrofit and rehabilitation of civil engineering structures.

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A state-of-the-art review of progress in this emerging and rapidly developing area in Russian Federation with an extensive list of citations is presented in [1]. By now many publications can be found on experimental and theoretical investigations aimed on obtaining of reliable data about behavior of steel-CFRP systems in tension, compression and bending ([2-9] etc.).

CFRP may be high strength (hsCFRP), high modulus (hmCFRP) and, most recently, ultra-high modulus (uhmCFRP). Generally an increase in CFRP stiffness is accompanied by a reduction in strength and rupture strain of the fibres and also by increase in cost. The modulus of the FRP selected for a particular application should be compatible with the substrate material for effective strengthening application. For this reason, CFRP materials should be used in most cases for steel substrate.

The key problem is connection between strengthened steel elements and CFRP reinforcement. Here may be distinguished relatively popular bonded and less developed unbounded joints. The application of first kind connections is overvelming in RC (reinforced concrete) elements strengthening.

Epoxy resin systems are most commonly used as the matrix in hand lay-up applications and as the adhesive in plate bonding techniques. Polyester resin systems are often used as the matrix material in preformed composite materials such as those used for plate bonding applications.

The epoxy resins are usually much stronger than concrete and in criteria of durability of connection destruction of a concrete surface dominates. The opposite situation takes place in case of steel. Here the adhesion layer is usually first to destruct and the most critical is shear stress as the tearing off stresses may be blocked somehow using additional fixation.

It should be noted that the adhesive layer material has no plastic properties and at ultimate strain the fracture takes place at the end of adhesion zone. It essentially reduces the load-carrying capacity of glued joints and limits prospects of it’s application in steel-composite connections. If a kind of yield plateau or a flat lot on the adhesive nonlinear stress-strain diagram occurs at some stress level it extends working length of connection in a glued joint. It can raise the strength of connection even for lower ultimate stress provided the ultimate strain is high. So the nonlinear properties of glue may be possibly of greater importance than the ultimate stress level.

Here the formulae for calculation of ultimate tension force and adhesion layer length with numerical examples are presented. These are based on linear elastic behavior of adhesive and connected materials (steel and CFRP) assumption. All relations are obtained as a result of integrating differential equilibrium equation (for example, [10]) for glue layer fragment with corresponding boundary conditions. The first problem is strengthening of locally damaged tension element. It is supposed that the damaged cross-section is cracked trough.

2. Tension element with through transverse defect

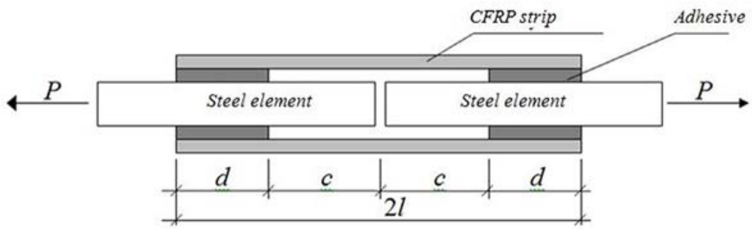

Fig. 1. Tension cracked steel element

Symmetrical strengthening with no secondary bending moments considered. The ultimate value of tension force may be determined from strength conditions of adhesive

$$P \le [P] = \frac{b_p}{\beta} \cdot R_{as} \tag{1}$$

$$\beta = \sqrt{\frac{G_a}{t_a} b_p \cdot \left(\frac{1}{E_s A_s} + \frac{1}{E_p A_p} \right)} \tag{2}$$

Nomenclature

R_{as}	glue material shear design resistance
R_{ay}	glue material design resistance
E_s	elasticity modulus of steel
A_s	reinforced beam cross-section area
E_p	elasticity modulus of composite tape material
A_p	tapes cross-section area
G_a	shear modulus of glue material
t_a	glue material layer depth
b_p	tapes width
α_p , α_s	thermal expansion factors of CFRP and steel elements respectively
ΔT_p , ΔT_s	temperature changes after reinforcement application in the CFRP and steel elements respectively
F_p , F_s	CFRP and steel tapes initial tension (before reinforcement application)
P	additional tensile force applied after reinforcement application

Minimal necessary glue layer length

$$d \geq d_{\min} = \frac{1}{2\beta} \ln \frac{1+Y}{1-Y} \tag{3}$$

$$Y \equiv \frac{b_p}{\beta} \cdot \frac{R_{as}}{P} \tag{4}$$

The effective (rational) for accepted value of $P \leqslant [P]$ glue layer length (further lengthening does not result in decrease of shear stress in glue) may be calculated by a number of iterations using the expression

$$\tau_{\max} = P \cdot \frac{\beta}{b_p} \cdot cth(\beta d) \leq R_{as} \tag{5}$$

It may be taken as approximately (3 to 4)$d_{\min}$ or more.

The worked Example 1

Conditions:

The two steel tapes of 50x5 cross-sectional dimensions are glued symmetrically on the top and bottom with two tapes of 50 mm width and 1.2 mm depth each (fig. 1). The necessary and effective bond layer lengths are to be defined for given assembly parameters.

Table 1. Steel element parameters:

b, mm	t, mm	A_s, mm^2	E_s, MPa	$(AE)_s$, N
50	5	250	206000	51500000

Table 2. CFRP tapes parameters:

b_p, mm	t_p, mm	A_p, mm^2	E_p, MPa	$(AE)_p$, N
100	1.2	120	300000	36000000

Table 3. Glue layer parameters:

G_a, MPa	t_a, mm	G_a / t_a	R_{as}, MPa
700	1	700	15

Calculations:

Using (2), β = 0.057478. Using (1), [P] = 26097 N. Accepted tension force value is P = 25000 N
Using (4), Y = 0.958. Using (3), $d_{\min}$ = 33 mm.
Using (5) :

Table 4.

d, mm	33	50	100	150	200
τ_{max}, mm	15.031	14.461	14.370	14.369	14.369

So, for given parameter values of bonded connection the ultimate applied tension force value is [P] = 26097 N. The minimum necessary length and the effective glue layer length to minimize shear stress in the glue layer are d_{min} = 33 mm and $d \approx$125 mm respectively for accepted applied tension force P = 25000 N.

Another possible application is CFRP strengthening of tension element with reduced cross-section along the reinforcement length.

3. Continuous tension element with reduced cross-section accounting for possible temperature variations and CFRP tapes prestress

The reinforcement is symmetrical without any secondary bending moments (Fig. 2). The ultimate value of additional tension force P may be determined from strength conditions at the ends of adhesive layer and those for steel and reinforcement tapes.

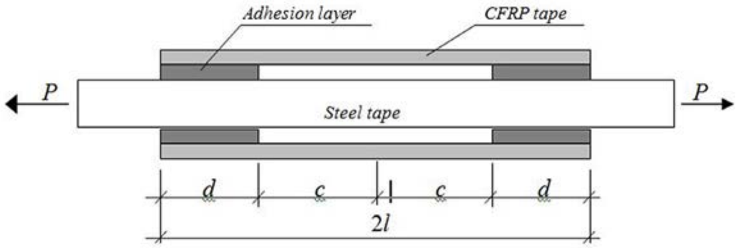

Fig. 2. Continuous tension element. P – additional tension applied after reinforcement

The strength condition for the left end (start point) of bond $\tau(x = 0) \leq R_{as}$ leads to expression for the ultimate value of additional tension force

$$P \leq [P] = R_{as} \cdot \beta \cdot \frac{t_a}{G_a} \cdot (AE)_s + R \cdot (AE)_s \tag{6}$$

$$(AE)_s = A_s E_s$$

$$R = -\left(\alpha_p \cdot \Delta T_p - \alpha_s \cdot \Delta T_s\right) + \left(\frac{F_p}{(AE)_p} - \frac{2 \cdot F_s}{(AE)_s}\right) \tag{7}$$

Furter, the shear stress in the adhesive layer at it's right end should be checked.

$$\tau(x = d) = \frac{1}{\beta} \cdot \frac{G_a}{t_a} \cdot \left(\frac{P}{(AE)_s} \cdot A1 + R \cdot (A2 - A1)\right) \leq R_{as} \tag{8}$$

$$A1 = ch(\beta d) - sh(\beta d)$$

$$A2 = \frac{\beta \cdot c}{(\beta \cdot c \cdot th(\beta d) + 1)}$$

The total applied force amounts $(F_s + P)$.

Other parameters were introduced in the previous examples.

Thermal expansion factors of CFRP may be taken as α_p =(-1-0) $\cdot$ 10^{-6} along the carbon fibre and α_p = (22-55) $\cdot 10^{-6}$ across it's cross-section. For steel α_s =12$\cdot$ 10^{-6} respectively.

The ultimate adhesive layer length $d_{\min}$ should be searched iteratively to meet it's shear strength condition at the ends $x = 0$ and $x = d$

$$\tau\left(x=0\right) \le R_{as} \quad \text{and} \quad \tau\left(x=d\right) \le R_{as} \tag{9}$$

Approximately it may be taken

$$\tau\left(0\right) = \frac{1}{\beta}\cdot\frac{G_a}{t_a}\cdot\left(\frac{P}{\left(AE\right)_s} - R\cdot\left(\frac{A2}{ch\left(\beta d\right)} - 1\right)\right) \tag{10}$$

The additional tension force P distribution between CFRP tapes (N_{pd}) and reinforced steel element (N_{sd}) along the unbounded length c between the glued ones d may be obtained from (14)-(15) as

$$N_{pd} = \frac{b_p}{\beta^2}\cdot\frac{G_a}{t_a}\cdot\left(\frac{P}{E_s A_s} - R\right)\cdot\left(1 - ch\left(\beta d\right)\right) + B\cdot\frac{b_p}{\beta}\cdot sh\left(\beta d\right) \tag{11}$$

where with sufficient accuracy may be taken

$$B = \frac{P}{\left(AE\right)_s}\cdot\frac{1}{\beta}\cdot\frac{G_a}{t_a} - R\cdot\frac{1}{\beta}\cdot\frac{G_a}{t_a}\cdot\left(\frac{A2}{ch\left(\beta d\right)} - 1\right)$$

and

$$N_{sd} = P + F_s - N_{pd} \tag{12}$$

The effective for a given value $P \leqslant [P]$ length of the adhesive layer (further increase does not decrease tension in the steel element) can be determined by successive iterations, using the above expressions (11) - (12).

It is also necessary to control the tension in the reinforced steel element and CFRP elements (N_{pd} / A_p and N_{sd} / A_s respectively).

The worked Example 3

Conditions:

The steel tape of 50x5 cross-section is bonded symmetrically on the top and bottom surfaces with two CFRP tapes each of 50 mm width and 1.2 mm depth (fig. 3). The ultimate value of additional tension force P should be determined. The necessary and the effective glue layer lengths are to be also defined.

The assembly parameters:

Table 5. Steel element parameters:

b, mm	h, mm	A, mm^2	E, MPa	$(AE)_s$, N	R_s, MPa	σ_s, MPa	F_s, N	α_s	ΔT_s, °C
50	5	250	206000	51500000	230	75	18750	1.20E-05	30

Table 6. CFRP tapes parameters:

b, mm	h, mm	A, mm^2	E, MPa	$(AE)_p$, N	R_p, MPa	σ_p, MPa	F_p, N	α_p	ΔT_p, °C
100	1.4	140	300000	42000000	2000	0	0	-1.00E-06	*30*

Glue layer parameters are the same as in Table 5 exept R_a = 14 MPa.

Calculations:

From (2), β = 0.0550081. From (7), R = 0.0003382. From (6), [P] = 74075 N. Accepted P = 70000 N

Using formulae (7 - 10), by values of d variation may be determined numerically it's minimum value to shear strength condition in the adhesive layer satisfy [d] = 44 mm.

The distribution of shear stresses along this length of the adhesive layer is shown in Fig. 3, *a*.

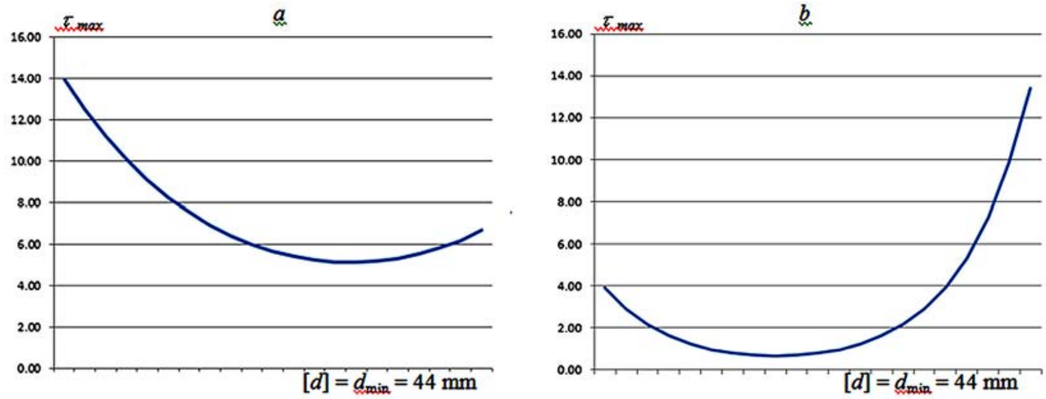

Fig. 3. Shear stress distribution: *a* - along the adhesive layer length $d = [d] = 44$ mm; *b* - along the adhesive layer length $d = [d] = 112$ mm

Easy to see in Fig. 3, that the requirement of shear strength in adhesive layer satisfies and there is still a certain margin of safety.

Further, using the formulas (16) - (17) the tension distribution is determined:

$N_{pd} = 31369$ N $\quad \sigma_p = 224$ MPa $<$ $R_y = 2000$ MPa

$N_{sd} = 57381$ N $\quad \sigma_s = 230$ MPa $<$ $R_y = 230$ MPa

Thus, for a given initial stress of the steel element and the temperature rise of +30°C the maximum additional tension force is about 5.738 - 1.875 = 3.863 tons, and the dominant factor in terms of strength criterion is not the adhesive layer but the steel member. The strength of the system as a whole can be provided by the redistribution of tension to CFRP elements having a larger margin of safety.

For temperature drop of -30°C the maximum additional tension force is $[P] \approx 7.00$ tons and the dominant factor in terms of strength criterion is again the steel member.

$N_{pd} = 31291$ N $\quad \sigma_p = 224$ MPa $<$ $R_y = 2000$ MPa

$N_{sd} = 57459$ N $\quad \sigma_s = 230$ MPa $<$ $R_y = 230$ MPa

The shear stress distribution along the length $d = [d] = 112$ mm of the adhesive layer is shown in Fig. 3, *b*.

For comparison it should be mentioned that the maximum elastic tensile force in the steel member without strengthening amounts 50 x 5 x 230 = 57500 N ≈ 5.87 tons.

4. Conclusion

In conclusion there may be outlined some essential points in respect to bonded CFRP reinforcement application for steel structural elements.

- This application may provide some limited positive effect. Yet the omitted in considered examples reduction safety factors are likely to worsen the design situations.
- This limitations result in particular from the lack of plastic properties of applied adhesives.
- The application of hybrid joints comprising some combination of bonded and non-bonded connections may improve the situation.
- In certain emergency cases bonded CFRP to steel connections may be surely effective as at least temporary measure to localize primary destructions.
- In steel structures the CFRP materials may serve as additional normally non-loaded reserve elements to increase the safety level.

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